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ABSTRACT

The observed day to day variability in the thermal structure of the top 200m water column at two stationary positions separated by a distance of about 440 km, along 89°E over the head of Bay of Bengal is studied with the aid of time series measurements of surface marine meteorological and Nansen Cast data collected during MONEX-79 experiment. The seasonal monsoon trough strengthened and gradually extended into the head Bay leading to the formation of a low pressure area during the period of study which subsequently deepened into depression. The cyclone heat potential registered a gradual increase at the northern location. Surface heat budget estimates are made to account the observed cooling of the sea surface and the deepening of the surface mixed layer. The observed vertical displacement in the thermocline does not appear to have been influenced by the prevailing surface wind stress curl. The spatial differences between the northern and southern locations are highlighted in terms of stronger stratification observed below the mixed layer at the northern location on account of its proximity to the mouth of the river Ganges, where abundant amount of fresh water discharge takes place.

Key-words: Thermal structure, Heat budget, Monex-79, Bay of Bengal.

INTRODUCTION

Monsoon depressions form over the northern Bay of Bengal during the summer monsoon season. While intensifying, these depressions usually travel north-westward and provide copious amount of rainfall for eastern and central India. The reasons for the formation of these depressions over the Bay of Bengal are not yet clearly understood. The importance of air-sea interaction processes and heat stored in the upper layers of the Bay of Bengal is also not adequately explored. To mitigate this situation, under the First Global Garp Experiment, a Monsoon Experiment (MONEX-79) was conducted over the Arabian Sea and the Bay of Bengal during 1979. Four Indian ships formed into a stationary polygon over the northern Bay of Bengal during last week of July 1979 were deployed to collect time series meteorological and oceanographic data to improve the understanding on the genesis and intensification of the monsoon depressions. Unfortunately, no depression formed during

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this observation period but the monsoon trough extended into the head, Bay of Bengal leading to the formation of a low. This low deepened into a depression on 6 August 1979.

DATA

Surface marine meteorological data collected at 3 hourly and Nansen Cast data at 6 hourly intervals from two ships occupying stationary positions 18°N & 89°E and 14°N & 89°E (Fig. 1.) from 24 to 31 July 79 were utilised to describe

![Map showing the stationary positions in the northern Bay of Bengal during Monex-79.](image)

the observed temporal variability. These stations are designated as IN and IS in the following discussion. The Nansen Cast data are interpolated at every 10 m using the three point Lagrangean interpolation formula. Wind data collected from two other Indian ships were also made use of to estimate the curl of the surface wind stress over the polygon.

Synoptic Weather from 24 to 31 July, 1979

The surface pressure analysis over the northern Bay of Bengal and the eastern India extracted from Indian Daily Weather Reports for the period 24-31
July 79 is shown in Fig. 2. On 24 July, the seasonal monsoon trough extended over the Indo–Gangetic plains and a feeble low appeared over Orissa. Weather improved during the following two days. On 27 July, the seasonal monsoon trough again extended into the head Bay of Bengal with an associated low pressure of 1002 mbs. This low pressure over the head Bay strengthened further in the following two days. This low moved westwards and lied off Andhra and Orissa coasts on 29 July. The monsoon trough experienced a mild weakening on 30 July and again strengthened on the following day. Lowest surface pressure of 998 mbs was observed over northwestern Bay of Bengal on 29 and 31 July. On the whole steady development of inclement weather can be noticed from 27 to 31 July. This low subsequently deepened into a depression and a severe cyclonic storm in the following few days (on 7 and 8 August, 1979).

**ANALYSIS AND DISCUSSION**

The daily march of surface pressure, wind speed and sea surface temperature (SST) at IN and IS is shown in Fig. 3. Lowering of pressure is noticed at both the locations. However, IN recorded a greater pressure drop probably on account of the extention of the monsoon trough into the head Bay of Bengal. The meridional pressure gradient significantly increased from the first to the last day on account of the strengthening of the monsoon trough. This feature is also clearly reflected in the near surface wind speed. Winds gradually
strengthened with time. On the whole, winds were stronger at IS compared to IN. In general the wind strength was more than doubled during this one week period. The SST at IS varied around 29°C with a mild cooling tendency throughout the observation period, while at IN, SST was always more than 29°C.
At IN a warming tendency was noticed during the first four days followed by a cooling tendency. Higher SST at IN over that of IS can be explained in terms of the thickness of the underlying ocean mixed layer and the net surface heat gain. The day to day variability observed in the SST can be explained in terms of the net heat gain at the air-sea interface and the thickness of the underlying mixed layer depth. The lateral Vergence of heat is assumed to be insignificant in the open ocean for short periods. Surface heat budget estimates are made following the procedure described by Rao, Ramam, Rao and Joseph (1985). Since no direct measurements of the solar radiation are available, values were estimated using the empirical relation following Laevastu and Hubert (1970). These heat budget estimates are shown in Fig. 4. The net surface heat gain \( Q \) is balanced against net insolation \( Q_i \), net long-wave radiation \( Q_b \), sensible heat flux \( Q_s \) and latent heat flux \( Q_e \); that is, \( Q = Q_i + Q_b + Q_s + Q_e \). Positive values imply heat gain to the ocean. The insolation at both the stations decreased from around 800 to 400 cal/cm²/day; that is, the magnitude of \( Q_i \) was halved during this one week period, probably due to the increased cloud cover in association with the strengthening monsoon trough. The cloudiness increased from 4 to 7 Octas at both the stations. The net long-wave radiation around -80 cal/cm²/day did not show any prominent changes. The sensible heat flux was relatively higher at IS compared to IN mainly due to greater air-sea temperature differences at the former. The \( Q_s \) values also showed a mild increasing tendency at IN during the latter half of observation period. This increasing tendency might foreshadow the onset of the disturbed weather conditions. Pant (1977) reported an increase in the sensible heat flux during the disturbed weather over the Arabian Sea during ISMEX-73 expedition. In the tropics, the latent heat flux is a very important process in the heat budget owing to its high magnitude. Both the locations have experienced increasing evaporation with time. The increasing tendency is noticed from the beginning at IS and from 27th onwards at IN. However, the evaporation shot up during the following four days at IN. This increase in evaporation is mainly caused due to the strengthened wind field. The net heat gain showed a rapid fall during the first few days mostly on account of the reduction in the insolation. The heat gain values were negative after 28th at IS and after 30th at IN on account of high evaporative heat loss. Greater net heat loss observed at IN can be attributed to the disturbed weather with the monsoon trough extending into the Bay of Bengal.

The influence of the net energy accumulated or depleted through all the radiative and turbulent heat flux terms at the sea surface on the properties of the upper boundary layer of the ocean is distinctly noticed. On the whole the cooling of the sea surface and deepening of the mixed layer is in conformity with the depleting tendency of net heat at the sea surface. The net heat loss at the sea surface promotes convective turnover enhancing the mixed layer depth. This would also result in the sea surface cooling. These features are well reflected in Fig. 5.
In the present study the mixed layer depth (MLD) is defined as the depth, where SST minus 0.2°C has occurred in the daily averaged vertical temperature profile. The mixed layer was deeper at IS compared to IN. The shallow mixed layer at IN might be attributed to stronger stratification caused by the fresh water discharge from the river Ganges. Consequently the vertical thermal gradient below the mixed layer was stronger at IN compared to than at IS. The MLD deepened by about 10m at both the locations. On the whole, the deepening of the mixed layer was also associated with an increase in the below layer gradient.

The vertical thermal structure of the top 200m water column observed at both the stations is portrayed in Fig. 6. Isotherms are drawn at 1°C interval for the daily averaged temperature data. Below the surface, thicker isothermal layer at IS over that of IN is prominently seen. Below this mixed layer, isotherms are relatively closely packed at IN compared to IS. This stronger thermal stratification might have been manifested due to strong halocline prevailing at the head Bay. The corresponding thermally stratified waters appeared at deeper depths at IS. Waters are relatively warmer throughout the 200m water column at IS compared to IN. This would probably induce eastward baroclinic circulation at the polygon area. Rao and Basil Mathew (personal communication) found convergence (estimated from USSR current meter records) over the same area at 25 and 50m depths from 13 to 18 July 1979, probably due to the influence of a clockwise gyral circulation forced by river discharges. The phase averaged temperature profiles at both the locations also clearly show the spatial differences (Fig. 7 a). The horizontal temperature difference was as high as 5°C around 70m depth. This horizontal thermal gradient decreased in the vertical on either side. It may further be conjectured here that relatively strong currents might prevail around 70m depth in the polygon area. The vertical thermal gradients corresponding to the phase averaged temperature profiles are shown in Fig. 7b. The magnitude and the depths of occurrence of the maxima of these gradients at both the locations distinctly differed. Below the depths of these maxima the thermal gradient was stronger over a thicker column of water at IN (45-90m) compared with that of IS (95-105m). Below 105m the magnitudes of thermal gradient converged to a single value around 200m depth at both the locations.

The vertical displacement of water in the thermocline is usually linked up to the near surface wind stress curl using the Ekman relationship. In the northern hemisphere clockwise curl induces sinking in the thermocline and vice versa. The observed vertical displacement of the thermocline is examined at both the stations (IN and IS) in relation to the curl of the surface wind stress (Table I) computed with the surface wind data from the ships at IN and IS and two other Indian ships which occupied eastern and western corners of the stationary polygon. The wind stress values are computed with a drag coefficient $1.4 \times 10^{-3}$ adapted from Rao and Basil Mathew (personal communication) who estimated following Kondo (1975). The curl values being positive (cyclo-
Table 1: The curl of the surface wind stress over the northern Bay of Bengal during 24-31 July, 1979.

<table>
<thead>
<tr>
<th>Date</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curl of the wind stress $\times 10^8$ dynes/Cm$^3$</td>
<td>0.49</td>
<td>0.47</td>
<td>1.35</td>
<td>1.23</td>
<td>2.29</td>
<td>1.64</td>
<td>0.91</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

Fig. 7. Mean vertical temperature profiles (24-31 July) at IS & IN
Fig. 8. Daily variation of $\text{CHP}_5$, $\text{HC}_{\text{ML}}$ & HC$_{200}$ at IS & IN respectively.

nic) strengthened from 24 to 28 July and weakened thereafter. However the observed concave shape of the isotherms in the thermocline at both the stations is not in conformity with the curl estimates. This disagreement calls for the importance of vergence in the upper layers probably under the influence of a clockwise gyral circulation at the head Bay.
The cyclone heat potential with respect to 28°C \((pC_p\int_{28}^{T} dz)\) estimated for IN and IS is shown in Fig. 8. At IN, the gradual increase in the heat potential till 29 July is a favourable trend for the development of disturbed weather. The formation of a low with a surface pressure of 998 mb on 29 July off Orissa coast might be linked up with this increase. Rao, Gopal Krishna and Babu (1981) also found a similar increase in the cyclonic heat potential at a station \((19^\circ N & 89^\circ E)\) in the head Bay before the formation of a monsoon depression during Monsoon -77. The fall in the heat potential on the following two days might have been caused due to increased surface heat loss. No significant changes in the heat potential values at IS are however noticed. The bulk heat content \((pC_p\int_{0}^{T} dz)\) of the mixed layer \((HC_{MLD})\) and of the 200 m water column \((HC_{200})\) are estimated for IS and IN and the temporal distributions are shown in Fig. 8. The spatial difference in the heat content of the mixed layer can be readily accounted in terms of the thickness of the layer at both the locations. The heat content of the layer also registered an increase due to the mixed layer deepening during this one week period. This increase acts as one of the favourable conditions for the formation and intensification of any disturbance over the sea (Gray, 1975). The hypothesis is found to be valid in the present case study as a low formed over the head Bay. The bulk heat content of the top 200m water column was on the whole higher at IS compared to IN as isotherms were found to deepen southward from the head Bay. The curves of \(HC_{200}\) corresponding to IN and IS are convex in shape due to descent of isotherms during the first half followed by ascent during the latter half. This would probably imply that the day to day variability observed in the bulk heat content is mostly governed by a vertical displacement of isotherms in the sea.

From the above study it can be briefly concluded that 1. during the observational period the surface pressure dropped at both the stations resulting in the strengthening of winds and cooling of the sea surface under the influence of monsoon trough extending over the head Bay;

2. the insolation decreased while the evaporation increased thus leading to depletion of net heat energy available at the surface during this one week period. On the whole, the heat gain was positive during the initial days and became negative during the last few days.

3. depleting tendency in the net gain contributed to the layer deepening of about 10m during this period at both the locations. The mixed layer was shallower at IN by about 30m over that at IS in view of stronger and thicker stratified waters prevailing below the mixed layer due to the fresh water discharges from the river Ganges.

4. the increasing tendency of temperature towards south from the head Bay might probably induce eastward baroclinic circulation with stronger speeds around 70m depth.

5. the vertical movement of the isotherms in the thermocline at IN and
IS was not in conformity with the sign and magnitude of the curl of the surface wind stress over the polygon and

6. the cyclone heat potential was found to increase at IN probably leading to the formation of a monsoon low over the head Bay. The day to day variability observed in HC at both the locations is found to be governed mostly by the vertical displacement of isotherms.

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